TORQUE - SPEED REGULATION OF DC MOTOR BASED ON LOAD TORQUE ESTIMATION METHOD

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-Abstract- As the output torque is regulated through the speed regulator in dc motor drive system, the speed response delays by the lag of the speed regulator when the load torque is imposed. When this load torque is directly measured or indirectly estimated, additional torque regulator which bypasses the speed regulator is possible and the improved speed response, such as the quick output torque response and small fluctuation of the motor speed, will become realized.

This paper proposes the torque-speed regulation which is based on the optimal control theory, in which the observer is used to estimate the load torque. This strategy also introduces the easy design of the speed regulator in dc motor drive system, as the desired system performance will be taken into account in the proposed quadratic performance index. A schematic design procedure based on this strategy and experimental examples are also shown.

1. INTRODUCTION

Recently not only classical control theory but also modern control theory can become applied to the various areas.[1-6] The modern control theory may be expected to have the large potentiality to improve the system performance in the drive applications. Moreover the design procedure is usually simplified in this modern control theory.

When the modern control theory is applied to the speed control of the separately excited dc motor, the plant system can be treated as a linear time-invariant system. This means that the pole-zero assignment is most important for the total system response. But conventional PI controller has less freedom in the control design procedure than the regulator based on the modern control theory. Besides various requirements to the system performance can be easily taken in the regulator design in the modren control theory.

This paper proposes the unified regulator design procedure based on the optimal control theory, in which the speed response to both the load torque and the speed reference can be specified independently. For this purpose, the suitable quadratic performance index is defined. As the result, concluded regulator based on this cost function can be classified into two subregulators. One is the speed regulator and the other is the torque regulator. As the augmented system, there is one series integrator, which allows no steady state offset. This type of controller is expected to be less sensitive to the system parameter variations. In the speed regulator, the state feedback of the measured quantity is necessary. In the torque regulator, the measured or the estimated load torque is effective for the better regulation. This load torque is defined as the uncontrollale but observable state variable, so the observer can be constructed to estimate its value with the ar itrary estimation time constant.

This method is also implemented and tested as shown in this paper.

2. LOAD TORQUE ESTIMATION

The impact of the load torque to the dc motor may give rise to the temporary speed drop. This is called impact drop. The recovery time of the speed is determined by the speed regulator, which is driven by the difference of the speed reference and the actual speed. But the optimal torque regulator, which can reduce this impact drop, is possible if the imposed load torque is directly measured or indirectly estimated. This new torque regulator is required to respond very rapidly, so the control signal of the torque regulator ought to bypass the speed regulator. As it is not economical and practical for the torque regulation to measure the load torque directly by the torquemeter, the indirect method to estimate the load torque should be adopted.

This estimation is made by the observer as follows.

DC motor is a dynamical system governed by the following state equation,

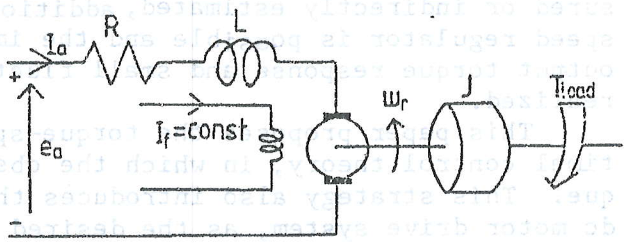


Fig.1 Simplified plant model of dc motor

$$\frac{d}{dt}\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{B}\,e_a + \mathbf{E}\,T_{load} \quad \text{—— (1)}$$

$$\mathbf{y} = \mathbf{c}\,\mathbf{x} \quad \text{—— (2)}$$

where

$$\mathbf{x} = \begin{bmatrix} I_a \\ \omega_r \end{bmatrix},\ \mathbf{A} = \begin{bmatrix} -\frac{R}{L} & -\frac{K_e}{L} \\ \frac{K_e}{J} & 0 \end{bmatrix},\ \mathbf{B} = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix},\ \mathbf{E} = \begin{bmatrix} 0 \\ -\frac{1}{J} \end{bmatrix},\ \mathbf{c} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad \text{—— (3)}$$

T_{load} is the imposed load torque to the dc motor. T_{load} is considered to be an unknown input, which is estimated by the zero-observer without steady state error.[4,6] The zero-observer is designed as follows,

$$\hat{T}_{load} = \frac{1}{s+a}\left[\, b\, I_a + \{\, c - d\,(\, s + a\,)\,\}\,\omega_r \,\right] \quad \text{—— (4)}$$

Using (4), the load torque is estimated as follows,

$$\hat{T}_{load} = \frac{1}{1+\tau s}\,T_{load} \quad \text{—— (5)}$$

Therefore the load torque can be estimated through the first order lag. τ is the time constant and may be chosen as an arbitrary positive constant. The parameters a,b,c and d are determined uniquely by the estimation time constant τ and motor parameters as follows,

$$a = \frac{1}{\tau}, \quad b = \frac{K_e}{\tau}, \quad c = \frac{J}{\tau^2}, \quad d = \frac{J}{\tau} \quad \text{—— (6)}$$

It is recommended to select time constant τ in relation to the poles of the total system. In this paper, τ is enough small to estimate the load torque as compared with the system time constant. The total schematic block diagram of the implemented observer is shown in Fig.2. This points out that the structure of this type of the observer is quite simple for realization.

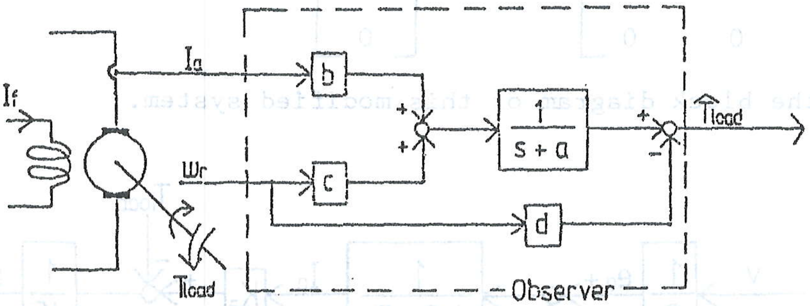


Fig.2 Schematic structure of load torque observer

3. SPEED REGULATION BASED ON OPTIMAL CONTROL THEORY

In order to suppress the impact drop, it is effective to use the additional torque regulator, which bypasses the speed regulator. The load torque is unknown input, and also is treated as the observable state variable in the dc motor system. When the speed reference and/or load torque are applied to the dc motor, equilibrium point of the state is changed according to the value of the load torque. The transient system performance is therefore represented as the loci of the all state variables from the initial state to the new equilibrium point. These loci are mainly determined through the performance of the speed regulator.

As the speed regulator can be independent from the torque regulator based on the observer, only the control poles, which govern the transient performance, are taken into account in the design of the speed regulator. Desirable poles are determined from the point of the total trade-off between the control energy and the system performance. Moreover it is required that all controllable state variables settle down at the equilibrium point in steady state.

For that purpose, the speed regulator should have one series integrator. This integrator also gives the better effect to the torque regulator because the system becomes less sensitive to the parameter variations. These requirements are reflected in the quadratic performance index. This cost function is constructed on the modified system, where one integrator is added as follows,

$$\frac{d}{dt}\bar{x} = \bar{A}\bar{x} + \bar{B}v + \bar{E}T_{load} \qquad (7)$$

$$\bar{y} = \bar{c}\bar{x} \qquad (8)$$

where

$$\bar{x} = \begin{bmatrix} \omega_r \\ I_a \\ e_a \end{bmatrix}, \quad \bar{B} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, \quad \bar{c} = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \qquad (9)$$

$$\bar{A} = \begin{bmatrix} 0 & \frac{K_e}{J} & 0 \\ -\frac{K_e}{L} & -\frac{R}{L} & \frac{1}{L} \\ 0 & 0 & 0 \end{bmatrix}, \quad \bar{E} = \begin{bmatrix} -\frac{1}{J} \\ 0 \\ 0 \end{bmatrix} \qquad \text{—— (9)}$$

Fig.3 shows the block diagram of this modified system.

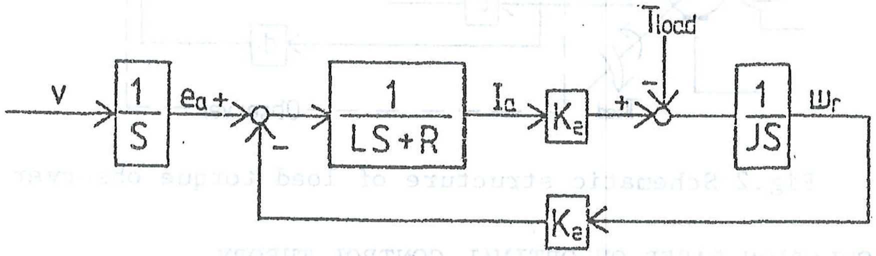


Fig.3 Block diagram of modified system

The quadratic performance index is made to have suitable weighting matrix in which the specified variables have strong weight. The system may be designed to have rapid rise time of motor speed due to the speed reference change and quick recovery time for the impact drop. So the following quadratic performance index Σ is employed.

$$\Sigma = \int_0^\infty (\bar{x}^T Q \bar{x} + v^T P v) \, dt \qquad \text{—— (10)}$$

here

$$Q = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \alpha^2 & 0 \\ 0 & 0 & 0 \end{bmatrix} \qquad \text{—— (11)}$$

The adjustment of parameters α and P will fix the control performance of the speed regulator. The solution to minimize Σ is realized in the following state feedback form.[7]

$$v_1 = -K_1 \omega_r - K_2 I_a - K_3 \int_0^t (\omega_r - \omega_r^{ref}) \, dt \qquad \text{—— (12)}$$

The constants of the feedback gains, K_1, K_2 and K_3 are conducted from the Riccati equation derived from (10).

Eq.(12) shows that the speed regulator has one series integrator as shown in Fig.4.

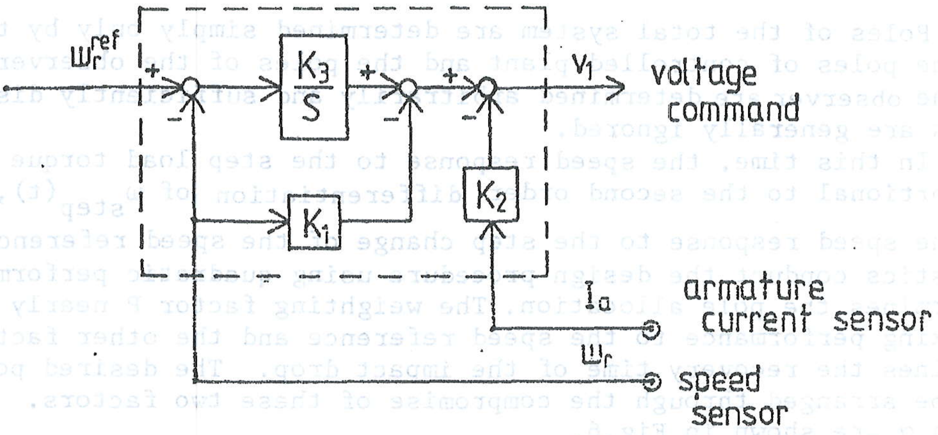


Fig.4 Schematic block diagram of speed regulator based on state feedback

4. DESIGN OF TORQUE - SPEED REGULATOR

The load torque functions as the initial deviation from the equilibrium point in the state space. The torque regulator intends to reduce this initial deviation so as to improve the transient performance. If the armature current is determined instantaneously, the estimated load torque can compensate the current in a moment and the initial deviation may be reduced small. So it is effective that the voltage command which drives the armature current corresponding with the estimated load torque is added to the output voltage command of the speed regulator. This former voltage command is the output of the torque regulator.

This final voltage command is represented as the sum of both commands. The addition of the torque regulator gives no influence on the response from the speed reference to the actual speed if parameters are correctly adjusted in the observer. The proposed torque-speed regulator is shown in Fig.5.

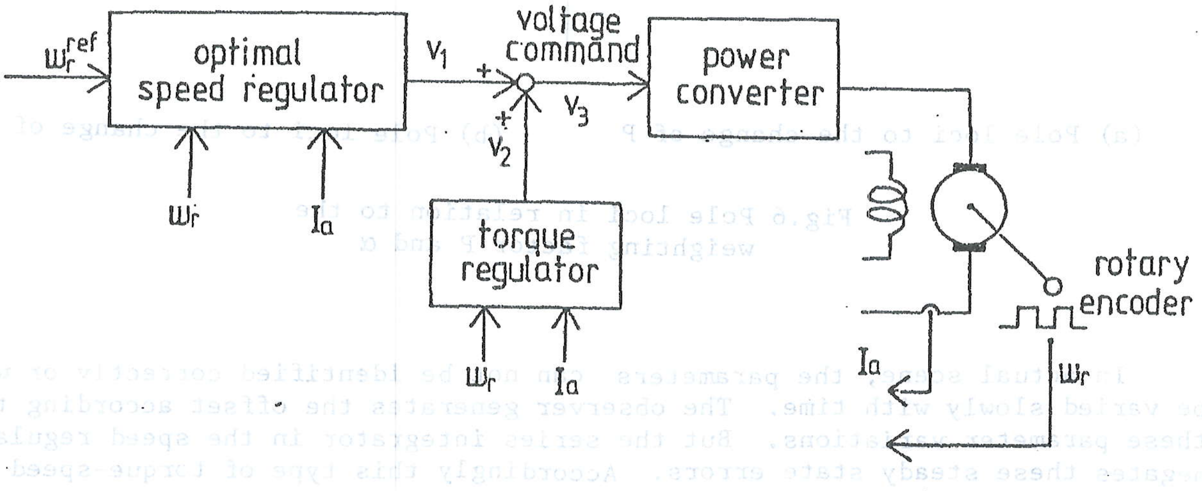
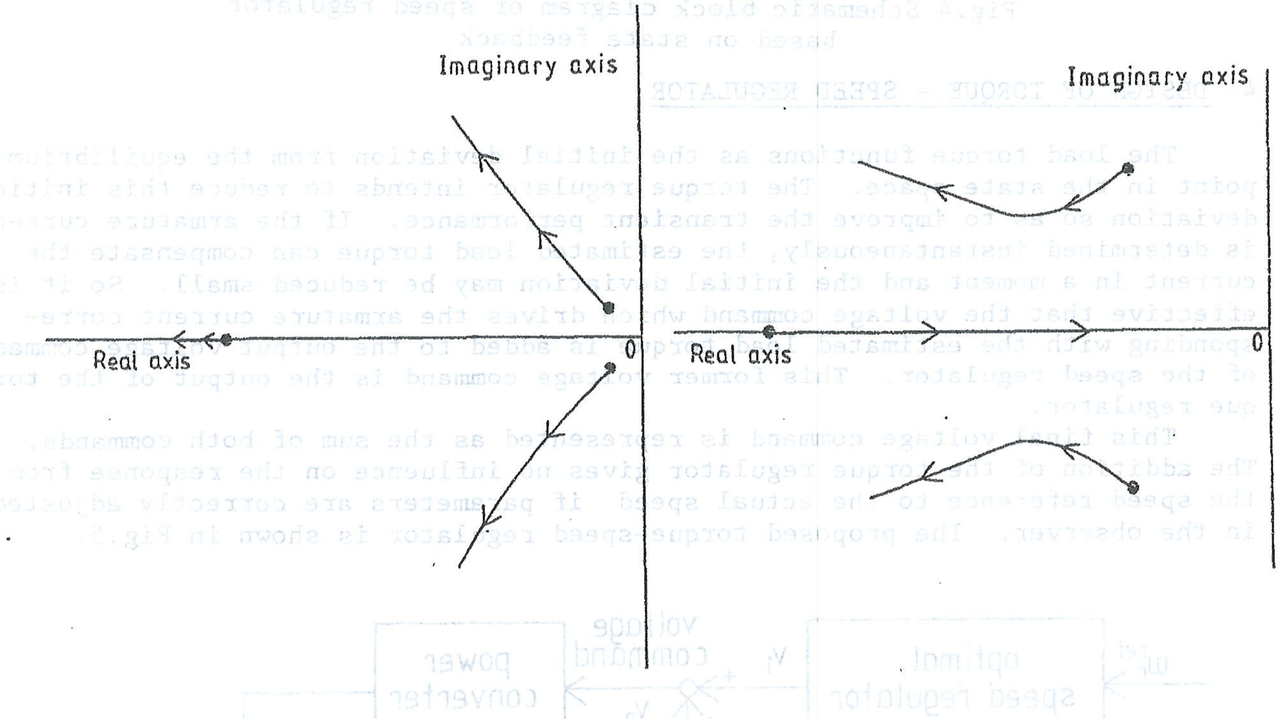


Fig.5 Torque-speed regulator based on load torque estimation method

Poles of the total system are determined simply only by the connections of the poles of controlled plant and the poles of the observer. As the poles of the observer are determined arbitrarily and sufficiently distant, these effects are generally ignored.

In this time, the speed response to the step load torque input is nearly proportional to the second order differentiation of $\omega_{step}(t)$, where $\omega_{step}(t)$ is the speed response to the step change of the speed reference. These characteristics conduct the design procedure using quadratic performance index which determines the pole allocation. The weighting factor P nearly determines the tracking performance to the speed reference and the other factor α nearly determines the recovery time of the impact drop. The desired pole assignment may be arranged through the compromise of these two factors. The pole loci by P and α are shown in Fig.6.



(a) Pole loci to the change of P (b) Pole loci to the change of α

Fig.6 Pole loci in relation to the weighting factor P and α

In actual scene, the parameters can not be identified correctly or will be varied slowly with time. The observer generates the offset according to these parameter variations. But the series integrator in the speed regulator negates these steady state errors. Accordingly this type of torque-speed regulator has no sensitivity of the steady state error.

5. NUMERICAL AND EXPERIMENTAL EXAMPLES

The proposed torque-speed regulator in Fig.5 is implemented and carried out as shown in Fig.7. The transistorized chopper is applied in this power converter. The nominal parameters of dc motor are shown in Table.1. The estimation time conatant τ is determined as 1 msec. The minimum time constant of total system is about ten times as large as τ.

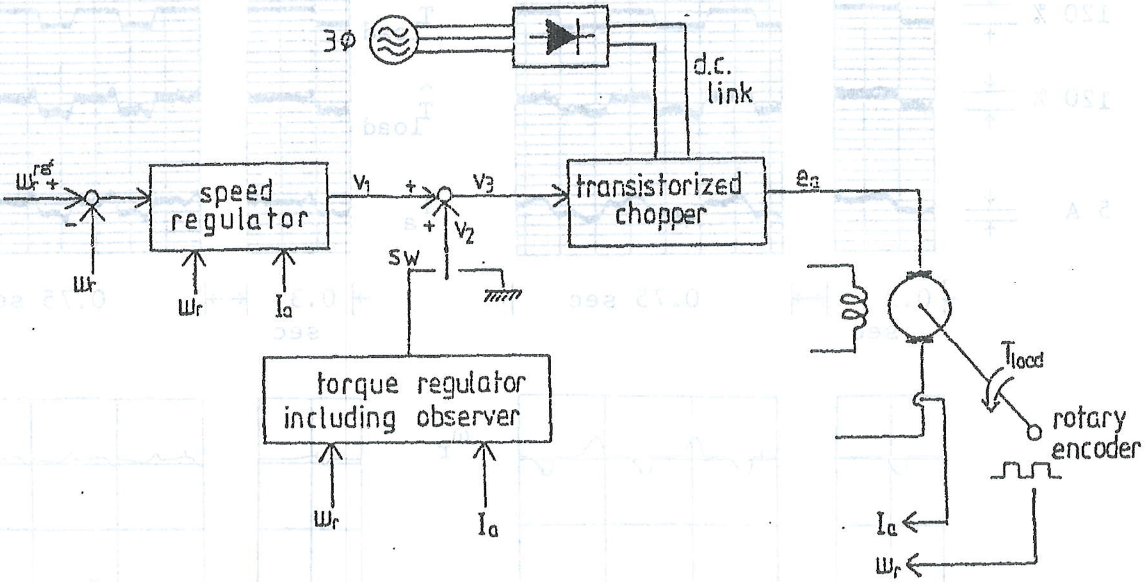
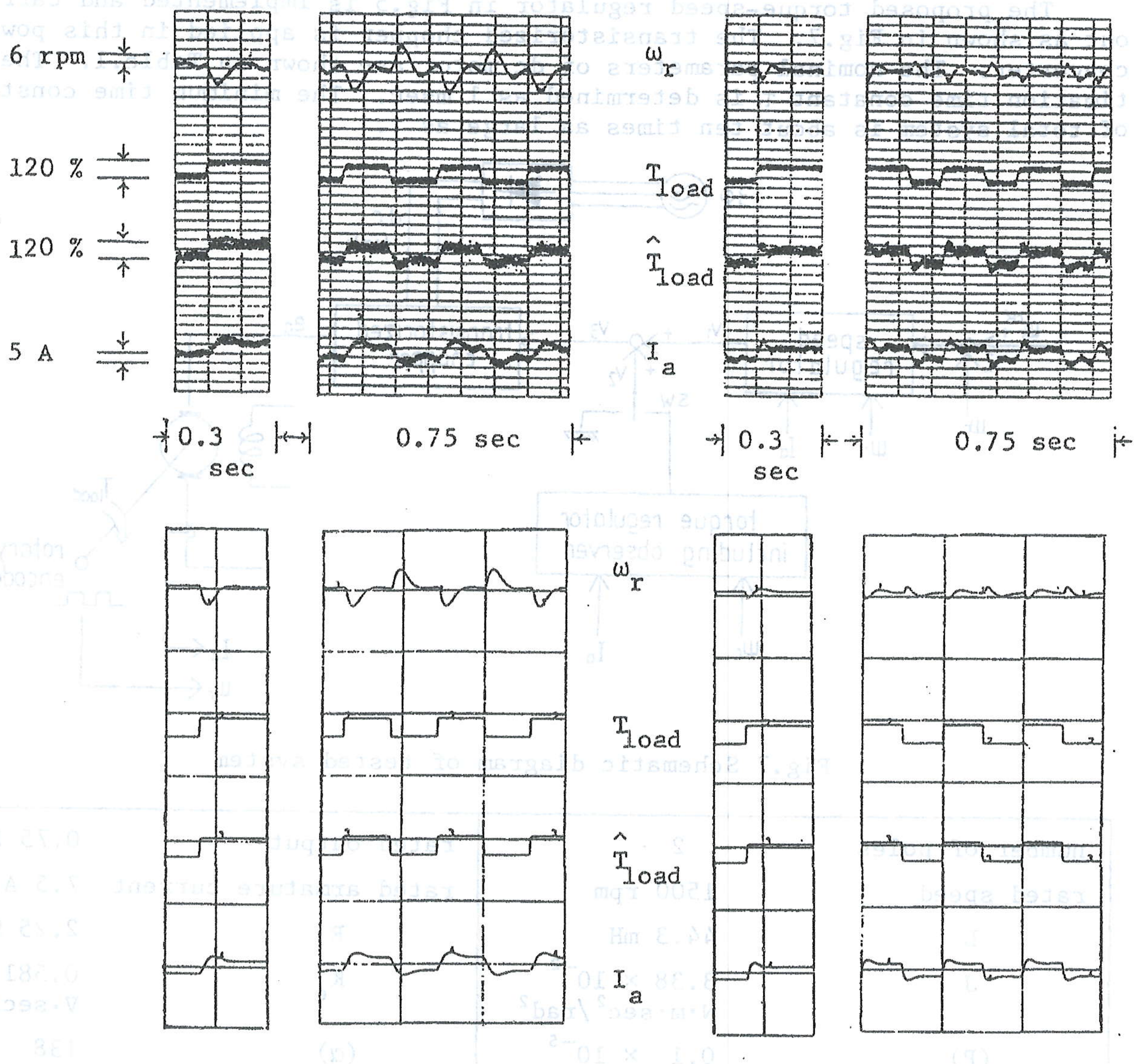


Fig.7 Schematic diagram of tested system

number of poles	2	rated output	0.75 kW
rated speed	1500 rpm	rated armature current	7.5 A
L	44.3 mH	R	2.25 Ω
J	3.38×10^{-2} $N \cdot m \cdot sec^2/rad^2$	K_e	0.581 V·sec/rad
(P)	0.1×10^{-5}	(α)	138

Table.1 Nominal parameters and weighting factors of tested dc motor drive system

Fig.8 shows the response of the rotor speed to the single and multiple step inputs of load torque. In Fig.8-(a), v_2 is zero so that the output signal of the torque regulator is not applied. In Fig.8-(b), v_2 is the output signal of the torque regulator. In this latter result, the fluctuation of the rotor speed can be reduced because of the torque regulator. The observer also well estimates the load torque as shown in this figure. These results show the augmented torque-speed regulator is quite effective for the impact drop and the well speed regulation.



(a) with only speed regulator (i.e. $v_2 = 0$)

(b) with proposed torque-speed regulator

Fig.8 Numerical and experimental examples of the response of the rotor speed to the single and multiple step load torque (up : measured , down : calculated)

6. CONCLUSION

The proposed torque-speed regulator is based on the modern control theory. The design is different from the conventional PI controller design. The speed regulator based on the state feedback with one integrator and the torque regulator based on the observer constitute the concluded total torque-speed regulator. The parameter sensitivity in the steady state is zero because of the series integrator of this speed regulator.

The total control system is simple and its design is easy, when it is based on the suitable performance index.

Numerical and experimental results show the validity of this type of the regulator.

NOMENCLATURE

L : armature inductance

R : armature resistance

$K_e \omega_r$: counter electromotive force

J : total inertia

T_{load} : load torque

I_a : armature current

e_a : armature voltage

I_f : field current

ω_r : rotor speed

s : Laplace operator

ω_r^{ref} : rotor speed reference

$\hat{T}_{load}$: estimated load torque

τ : estimation time constant

Σ : quadratic performance index

P, α : weighting factor in the performance index

v_1 : output signal of speed regulator

v_2 : output signal of torque regulator

v_3 : voltage command

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